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Patentanmeldung Nr. **Patent application No.** **Demande de brevet n°**

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Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

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(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
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METHOD AND SYSTEM FOR DETERMINING PORE FLUID PRESSURE IN A SUBSURFACE FORMATION

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METHOD AND SYSTEM FOR DETERMINING PORE FLUID PRESSURE IN A SUBSURFACE FORMATION

The invention relates to a method of détermining a pore fluid pressure in a region of interest in a subsurface formation. The invention also relates to a system for determining a pore fluid pressure.

Generally, the pore fluid pressure in a subsurface formation is determined with a so-called repeat formation test within the region of interest, or particularly within a depth range of interest.

In particular in the field of exploration drilling, there is a desire to predict the pore fluid pressure in the region of interest that lies ahead of the drill bit. It is particularly desirable to be able to predict a region of over pressure in the formation, for an over pressure can give rise to influx of formation fluid in the bore hole, a so-called kick which can result in a blow-out.

Currently available pore fluid pressure prediction techniques in the art are normally based on determining a deviation in the porosity from a normal compaction trend of the formation, which determines the porosity. Such a technique is thus based on determining undercompaction and is referred to as an undercompaction technique. In such techniques it is generally assumed that over pressure is associated with abnormally high sediment porosity. However, over pressure does not always have a strong porosity-based signature, because over pressure can be caused by varying geological processes and are

frequently related to complex geological structures, such as diapirs and overthrusts.

It is therefore an object of the invention to provide a more reliable method for determining a pore fluid pressure in a region of interest.

In accordance with the invention, the pore fluid pressure in a region of interest in a subsurface formation below the earth surface is determined in a method wherein a stress value representative of formation stress is determined in a measurement region of the subsurface formation being located displaced from the region of interest, and the stress value is used for determining the pore fluid pressure in the region of interest.

It has been found that the formation stress in a region that is displaced from the region of interest, is affected by the formation pore fluid pressure in the region of interest. The invention is based on the insight that, by observation of the formation stress in the measurement region, information on the pore fluid pressure in the region of interest can already be obtained outside the region of interest. For instance, pore fluid information in a region that has not yet been reached in a drilling operation can therefore be obtained.

The method of the invention is stress-based rather than porosity based, and therefore it is less dependent of porosity than is the case in undercompaction techniques. Therefore, the method of the invention can be utilized on its own merits, or as a complementary technique in combination with existing methods.

The region of interest may be a subsurface hydrocarbon reservoir.

The invention is particularly advantageous in a case where the pore fluid pressure in the region of interest is an over pressure, being a pore fluid pressure that is higher than the purely hydrostatic pressure, because the stress in the region of measurement can then be used to predict the over pressure and thereby a kick during drilling can be avoided. If successfully applied prior to drilling, the method will assist in exploration of hydrocarbons in high pressure regions an in optimum well design.

In an embodiment of the invention, the use of the stress value for determining the pore fluid pressure in the region of interest includes determining an effective stress value representative of the difference between the formation stress in the measurement region and a value of pore fluid pressure in the measurement region.

A determination of effective stress is often simpler and takes less rig time in a drilling operation than a true stress measurement. Moreover, since the true stress in the measurement region adjacent to for instance an over pressure region already increases while the pore fluid pressure in the measurement region may still be hydrostatically determined, the effective stress is usually more sensitive than the true stress for abnormal changes in the pore fluid pressure in the displaced region of interest. Therefore, an over pressure in the region of interest is accurately predictable by an increase in the effective stress value just adjacent the onset of the over pressure region.

In an embodiment of the invention, determining the stress value includes determining stress value representative of a principal formation stress in one of

one of the three principal stress directions in the stress tensor.

The principal direction can be selected to provide an optimal sensitivity in the measurement region to an abnormality in the pore fluid pressure in the region of interest. It has been found that the minimal principal stress direction provides the most optimal sensitivity. Often, the minimal principal stress direction coincides with the horizontal direction.

In an embodiment of the invention, two or more stress values or effective stress values, are determined, each at a different depth in the measurement region. Herewith a depth-survey can be produced.

In particular, a variation of the two or more stress values or effective stress values as a function of their depths is determined, and compared to a nominal value. By monitoring a deviation from the nominal value, information is obtained about a possible abnormality in the pore fluid pressure in the region of interest.

Preferably, three or more stress values or effective stress values are determined, which allows for determining a deviation from a trend in a depth-survey in the measurement region. Such a deviation from a trend can contain pore fluid pressure information relating to the region of interest.

Suitably, a deviation of the pore fluid pressure in the region of interest from the hydrostatical pore fluid pressure in the region of interest is determined.

Prior to determining the pore fluid pressure in the region of interest in a way as defined above:

- a drill bit can be provided on a lower end of a drill string; whereby

- the lower end of the drill string is lowered in a bore hole in the subsurface formation;

while during determining the pore fluid pressure in the region of interest:

- the drill bit can be operated to deepen the hole.

During drilling a bore hole the region of interest can be the region that is about to be drilled. This method can therefore be used to obtain an early warning during a drilling operation of a sudden abnormality in the pore fluid pressure in the region that is about to be drilled. This warning sign can be used to avoid a kick can be avoided in case that the abnormality is an over pressure, or formation damage by intrusion of drilling fluid can be avoided in case that the abnormality is an under pressure.

The invention is also embodied in a system for determining a pore fluid pressure in a region of interest in a subsurface formation below an earth surface, the system comprising:

- a measurement arrangement for producing a signal representing a stress value representative of the formation stress in a measurement region of the subsurface formation; and
- a signal processing device arranged to receive the signal and utilize the signal to determine the pore fluid pressure in the region of interest, which region of interest is located displaced from the measurement region.

The measurement system can, for instance, be a system suitable for remote geophysical determination techniques, such as a 4-D seismic technique or time-lapse seismic technique, because the signal produced can be processes to procure a pore pressure in the region of interest.

The measurement system preferably includes at least a measurement-while-drilling device that is installable on a drill pipe for lowering into a bore hole such that the measurement while drilling device can reach the measurement region. For the purpose of this specification, a measurement-while-drilling device is to be construed to include a measurement-ahead-of-the-bit device, whereby the measurement region lies ahead of the measurement-ahead-of-the-bit device when seen in drilling direction.

These and other features of the invention will be elucidated below by way of example and with reference to the accompanying drawing, wherein

Figure 1 shows a schematic example of pore fluid pressure and principal stress evolution over depth in a subsurface formation;

Figure 2 shows a schematic example of the effective principal stress for the case of Figure 1;

Figure 3 (parts a and b) shows field data of (a) pore fluid pressure and true formation stress and (b) corresponding effective horizontal stress in an example bore hole (data from J.S.Bell, in proceedings of "Rock at Great Depth", Balkema Rottedam, 1990); and

Figure 4 (parts a and b) shows (a) schematic representations and (b) field data of a sonic analysis from seismic interval velocities as compared to the pressure profile (data from J.P. Mouchet and A. Mitchell in "Abnormal pressures while drilling" from Elf Aquitaine Manuals Techiques 2, 1989).

In the drawing, like reference numerals refer to like features.

Figure 1 schematically shows the pore fluid pressure (line 1) and the true minimum principal stress (line 2),

as a function of depth in a subsurface formation below the earth surface. The lines are a schematic example for purpose of explaining the invention. Examples of measured data will be shown below.

At shallow depths, down to the depth indicated by the dashed line 4, the pore fluid pressure increases essentially hydrostatically with depth. Dashed line 4 corresponds to the top of an over pressure region, and the pore fluid pressure increases at a higher rate than the hydrostatic rate at depths below the dashed line 4.

As can be seen in Fig. 1, the true minimum principal stress (line 2) also increases at a higher rate than is the case for shallow depths, but the high rate of increase already starts at a shallower depths than the onset of the over pressure region that is indicated by dashed line 4.

Apparently, the pore fluid pressure and the formation stress are not only coupled within the same region of the formation as has been known and modelled before, but the formation stress in a region above the region of interest is affected by an abnormality in the pore fluid pressure in the region of interest. The invention is based on utilizing this observation, in that the pore fluid pressure in a region of interest in a subsurface formation below the earth surface is determined using the formation stress in a measurement region that is displaced from the region of interest.

In a case where the pore fluid pressure in the region of interest is relatively low, for instance due to depletion of a hydrocarbon reservoir, there can be a so-called arching effect in the formation above the region of interest leading to a measurable effect in the stress in the formation above the region of interest. Although

other factors may be determined to cause the same effect, it is presently suggested that in the opposite case of an over pressure in the region of interest, the measurable effect in the stress in the formation above the region of interest may be due to a so-called reversed arching effect. The signature in the stress measurements in the measurement region may be different in respect of under pressure and over pressure.

In Figure 2 is can be seen that the corresponding effective principal stress (line 3), which is here taken to be the minimum principal stress minus the pore fluid pressure at the same depth, shows a pronounced peak at the onset of the over pressure region which is indicated by the dashed line 4. In other words, the onset of the over pressure region appears as a reversal in the effective principal stress signal.

Figure 3 shows example field results of various tests relating to formation stress determination and pore fluid pressure determination in a subsurface bore hole. The following table explains the symbols used.

Reference numeral	Test or physical entity
9	Drill stem test
10	Repeat formation test
11	Leak off test
13	Initial feedrate pressure
14	Overburden pressure

Line 14 indicates the mud weight pressure in the bore hole. As can be seen by symbols 10 in figure 3a, at a depth of 4095 m an over pressure region starts. At a depth of approximately 3700 m, i.e. some 400 m above the onset of the over pressure region, the minimum (horizontal) stress starts to deviate from a straight line. This is more readily observable in figure 3b, where

the effective minimum stress is depicted. This graph shows a pronounced peak starting at 3700 m. Thus the minimum stress determination, or preferably the effective minimum stress determination, can be utilized to predict the upcoming abnormality in the pore fluid pressure at deeper depth.

It is remarked that additional field data has been disclosed in the mentioned article by J.S.Bell, in particular in figure 14 which is herewith incorporated by reference.

Based on field data, it is now generally concluded that the peak in the effective minimum stress becomes apparent starting from tens to hundreds of meters above the onset of an over pressure region. It is clear that in a case of drilling a new bore hole, the increase in the principal stress rate in depth can be used as a warning signal for an over pressure region that is about to be reached, so that a kick can be avoided by selecting and circulating an appropriate increased mud density for continued drilling.

Line 5 in figure 4a schematically shows an effective principal stress as a function of depth, similar as shown before. The approximate onset of the over pressure region is as before indicated with a dashed line 4. Line 6 in figure 4a schematically shows the sonic signal (or seismic velocity), which also reveals a reversal of the signal at the depth indicated by dashed line 4.

An example of a measurement is shown in figure 4b, wherein symbols 15 represent data points taken by logging the shales in the well, and line 16 is a pseudo-sonic from a seismic model. The reversal in the sonic signal is seen at 7. The right hand side of the figure 4b shows the corresponding pressure profile and a pressure trend 18

from a model. The dashed line 17 represents the top of an undercompaction. Dashed line 4 indicates that just below the signal reversal 7 an abnormal profile indicative of an over pressure region is present. It is therefore concluded that geophysical measurements such as seismic measurements or sonic measurements can be used for determining the formation stress for pore fluid pressure prediction as described herein.

In practice, the method described above can be used during a drilling operation, particularly during an exploration drilling operation, to provide a pore fluid pressure prediction ahead of the drill bit. A drill string may be used that is provided with a measurement while drilling sub for providing a stress signal from which the formation stress can be determined. The stress signal can then be utilized to predict the pore fluid pressure in a region ahead of the drill bit.

The method described above can also be used prior to drilling using for instance 4-D seismic data to assist in exploration and well design in high pressure fields.

C L A I M S

1. Method of determining a pore fluid pressure in a region of interest in a subsurface formation below an earth surface, wherein a stress value representative of formation stress is determined in a measurement region of the subsurface formation being located displaced from the region of interest, and the stress value is used for determining the pore fluid pressure in the region of interest.

2. The method of claim 1, wherein the measurement region of the subsurface formation is located less deep as seen from the earth surface than the region of interest.

3. The method of claim 1 or 2, wherein using the stress value for determining the pore fluid pressure in the region of interest includes determining an effective stress value representative of the difference between the formation stress in the measurement region and a value of pore fluid pressure in the measurement region.

4. The method of any one of claims 1 to 3, wherein determining the pore fluid pressure in the region of interest includes using a geo-mechanical model of the subsurface formation.

5. The method of any one of the previous claims, wherein determining the stress value includes determining a principal stress value representative of the horizontal formation stress in the measurement region.

6. The method of any one of the previous claims, wherein determining the stress value includes performing a geophysical measurement, such as a seismic measurement or a sonic measurement, to obtain geophysical data, and

processing the geophysical data to obtain the stress value.

7. The method of any one of the previous claims, wherein two or more stress values are determined, each at a different depth in the measurement region.

8. The method of claim 7, wherein effective stress values are determined for each of the stress values, which effective stress values are representative of the difference between the formation stress at the corresponding depths in the measurement region and the value of the pore fluid pressure at substantially the same depth in the measurement region.

9. The method of claim 8, wherein a variation of the two or more effective stress values as a function of their depths is determined, and compared to a nominal value.

10. The method of any one of the previous claims, wherein a deviation of the pore fluid pressure in the region of interest from the hydrostatic pore fluid pressure is determined.

11. The method of claim 10, wherein an overpressure in the region of interest is determined.

12. The method of any one of the previous claims, wherein prior to determining the pore fluid pressure in the region of interest:

- a drill bit is provided on a lower end of a drill string; and
- the lower end of the drill string is lowered in a bore hole in the subsurface formation,

and wherein during determining the pore fluid pressure in the region of interest:

- the drill bit is operated to deepen the hole.

13. System for determining a pore fluid pressure in a region of interest in a subsurface formation below an earth surface, the system comprising:

- a measurement arrangement for producing a signal representing a stress value representative of the formation stress in a measurement region of the subsurface formation; and
- a signal processing device arranged to receive the signal and utilize the signal to determine the pore fluid pressure in the region of interest, which region of interest is located displaced from the measurement region.

14. The system of claim 13, wherein the measurement system includes at least a measurement-while-drilling device that is installable on a drill pipe for lowering into a bore hole such that the measurement-while-drilling device can reach or approach the measurement region.

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A B S T R A C T

METHOD AND SYSTEM FOR DETERMINING PORE FLUID PRESSURE IN A ROCK FORMATION

Method of determining a pore fluid pressure in a first region of a subsurface formation, wherein a stress value representative of formation stress is determined in a second region of the subsurface formation being located displaced from the first region, and the stress value is used for determining the pore fluid pressure in the first region.

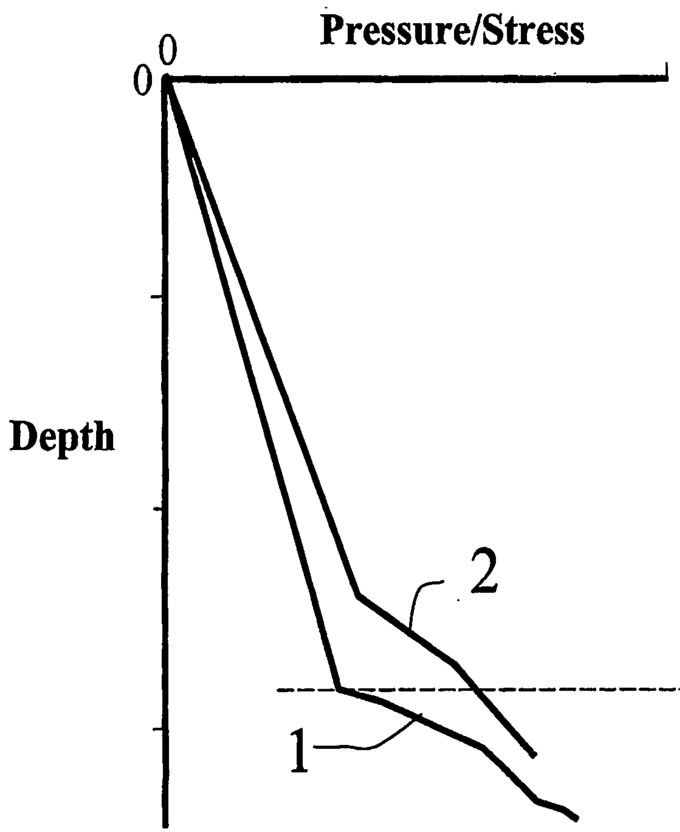


Fig. 1

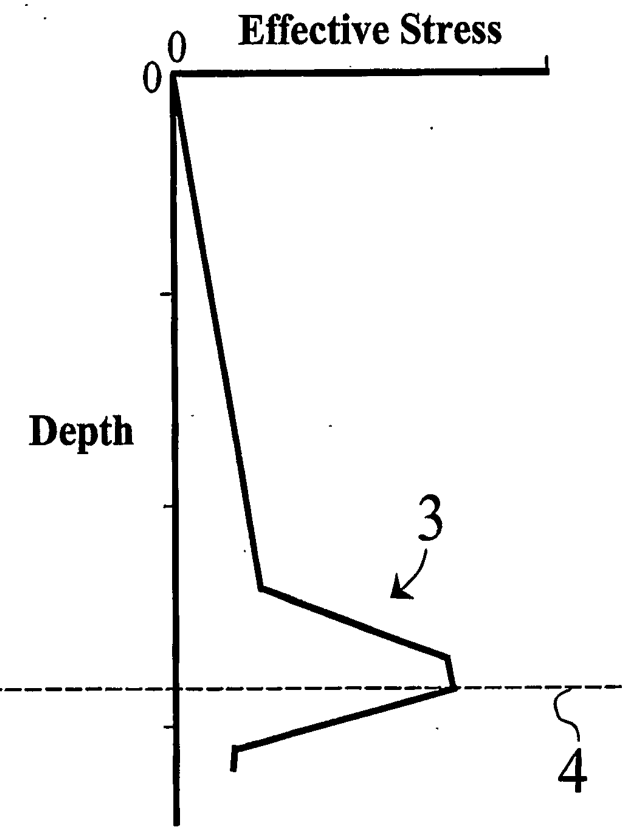
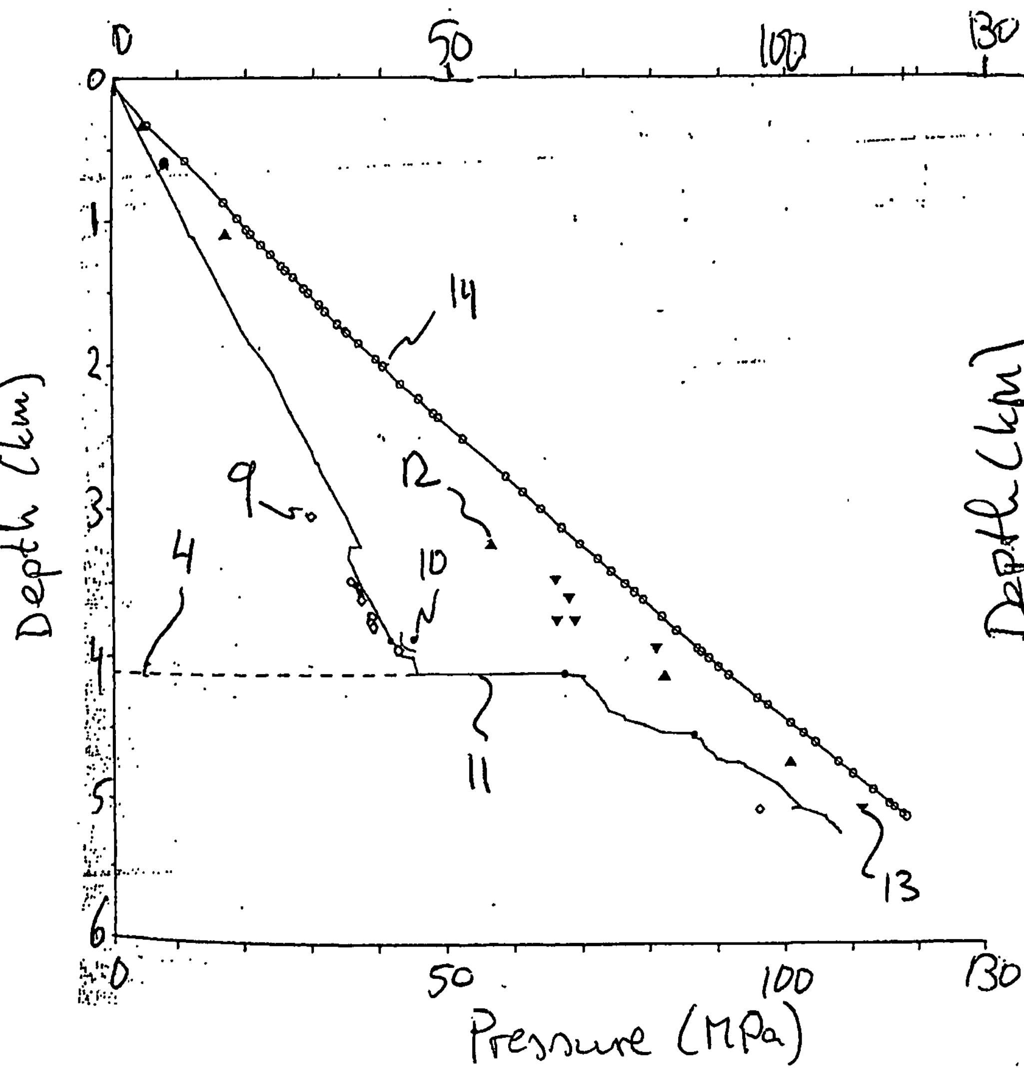
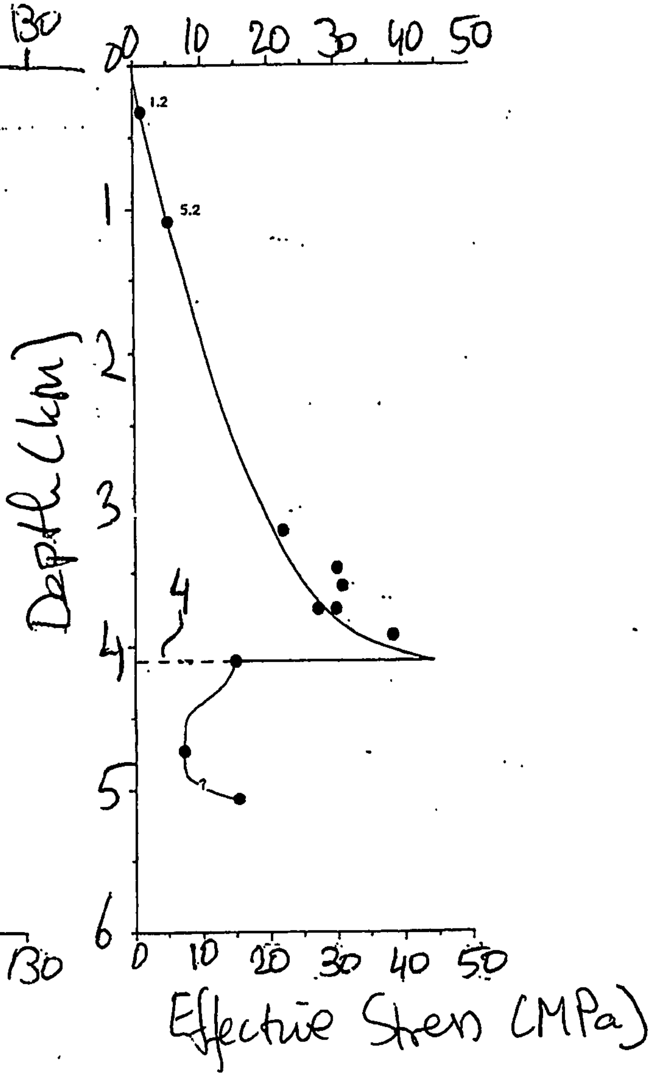


Fig. 2



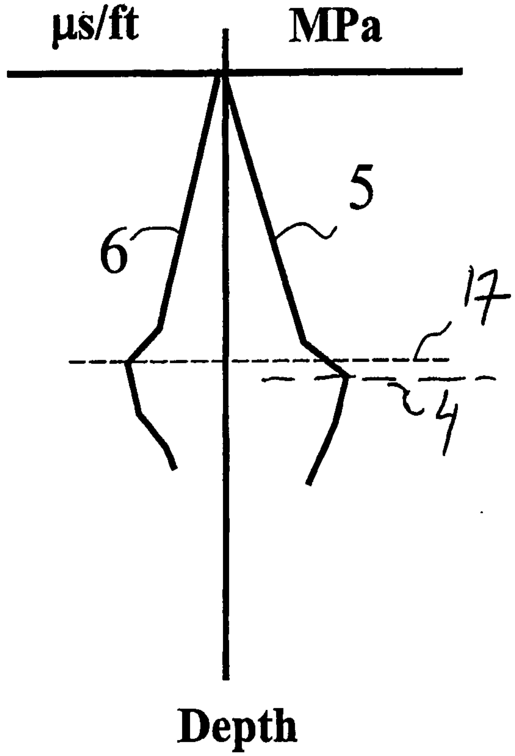
Depth (km)
Pressure (MPa)
0
50
100
130
1
2
3
4
5
6
4
9
10
11
12
13
14

Fig. 3a



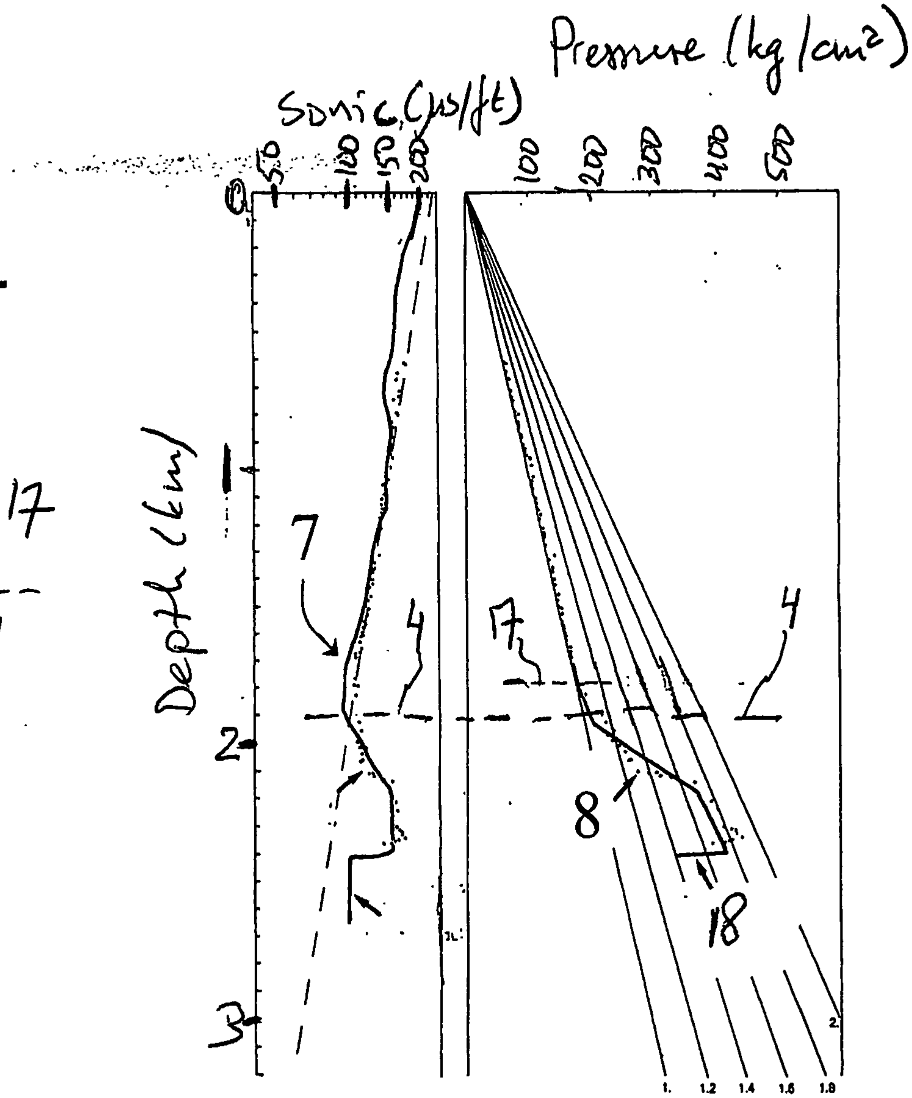
Depth (km)
Effective Stress (MPa)
0
10
20
30
40
50
1
2
3
4
5
6
1.2
5.2
4

Fig. 3b



µs/ft
MPa
5
6
17
4
Depth

Fig. 4a



Pressure (kg/cm²)
Sonic (µs/ft)
50
100
150
200
100
200
300
400
500
Depth (km)
0
1
2
3
7
4
17
4
8
18
1.
1.2
1.4
1.6
1.8
2

Fig. 4b

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